The Nature of Absolute Zero Temperature

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Abstract

Absolute zero temperature (*0 K*) is the lowest limit on the thermodynamic temperature scale. Its theoretical value (around *-273.15 °C*) is predicted by extrapolating the ideal gas law. However, the nature of absolute zero is often misunderstood due to the common misconception that temperature reflects the average kinetic energy of particles in a system. In reality, temperature measures thermal energy, the dynamic fraction of a system's internal energy. Internal energy should be defined as the total energy within a system, as described by the mass-energy equivalence principle ($E = mc^2$). This energy can be unlocked through various processes such as chemical or nuclear reactions. In matter-antimatter annihilation, the entire energy of matter can be released. The potential energy of bonds can be unlocked through nuclear and chemical reactions. Bonds behave like springs, storing energy when work is done to stretch them. Additionally, energy can be stored in excited electrons, which move to higher orbitals when they absorb energy. A portion of a system's internal energy may be exchanged with its surroundings through spontaneous processes, such as nuclear fission or electron orbital transitions. During this exchange, some of the energy is converted into the kinetic energy of particle motion. This dynamic portion of internal energy constitutes the thermal energy that directly influences temperature measurements. This dynamic energy is typically unlocked from a system's internal energy through spontaneous processes, such as chemical and nuclear reactions. An absence of dynamic energy corresponds to the absolute zero temperature as thermal energy is undetectable. Essentially, absolute zero temperature characterizes a specific system state, typically at its lowest potential energy, where no reaction or spontaneous process can further convert its internal energy into thermal energy. Kinetic energy is one form of dynamic energy that derives from and tends to equilibrate with potential energy in a system, creating the delusion of a correlation with temperature. Indeed, kinetic energy is not necessarily zero even at a ground state; for instance, electrons still exhibit orbital motion.

Introduction

The concept of absolute minimum temperature dates back to 1665 in Robert Boyle's work: "New Experiments and Observations Touching Cold".[1] This temperature was initially predicted through Charles's law of volume, which states that the volume of gases tends to expand when heated and is proportional to temperature.[2-3] According to this law, the volume of gases would theoretically reach zero at a temperature of around *-273.15 °C*, which is commonly regarded as the lowest possible temperature and defined as absolute zero, or *0 K*.[4-7] However, the physical nature of this minimal temperature is not fully understood. It is often assumed that at absolute zero, fundamental particles exhibit minimal vibrational motion. This notion is a misconception related to the representation of temperature. Temperature cannot fully represent the average kinetic energy of a system; rather, it relates to the thermal energy in a system, primarily measuring the emission level released in potential energy.[8] This article seeks to clarify the physical nature of absolute zero temperature.

New Definition of Internal Energy

Temperature relates to the internal energy of a system. However, the concept of internal energy remains nebulous. Let's delve deeper into the essence of internal energy to clarify its nature. According to Einstein's mass-energy equivalence principle,[9] the total energy of a system is proportional to the mass of the system given by the form of

$$(1) \qquad E = mc^2$$

where *c* denotes the speed of light and *m* represents the effective or equivalent mass of the system. This equation reveals a fundamental principle of nature: mass and energy are equivalent and can be transformed into one another.[10]

For a system at rest relative to an observer, there is no relative motion, so the system has neither momentum nor kinetic energy from the observer's perspective. In this case, the system's equivalent mass *m* is equal to its rest mass m_0, and its total energy will be m_0c^2 according to the equation. However, if the system is in motion relative to the observer, it possesses kinetic energy, which adds to its total energy and equivalent mass. This means that both the total energy and the observed mass of the system increase due to its motion, indicating that kinetic energy and system mass are interchangeable. This relation can also extend to massless systems, such as photons.

For a many-body system, such as a container of gas, the mass-energy equation is generalized to the energy-momentum relation:

$$(2) \qquad E^2 = (pc)^2 + (m_0c^2)^2$$

where *p* denotes the total momentum of the particles. This extension applies to systems with or without rest mass. For a massless system ($m_0 = 0$), its energy becomes $E = pc$, the same as the energy of a photon. For a system with nonzero rest mass ($m_0 \neq 0$), the momentum term $(pc)^2$, representing the kinetic energy of particle motion relative to the mass center of the system, contributes to the total energy and mass of the system. In the case of a stationary system ($p = 0$), the equation simplifies to the familiar form of the mass-energy equation (1).

Indeed, for a single-body system, Equation (2) can be simplified to Equation (1) by substituting the momentum term (*p*) definition:

$$(3) \qquad p = mv$$

and the relativistic mass term (*m*):

$$(4) \qquad m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where v denotes the speed of the body in the system. This demonstrates that the energy-momentum relation is more general than the mass-energy equation, as it applies to systems involving multiple bodies. It also demonstrates the interchangeability between mass and energy even to an observer stationary to a system.

The mass-energy interchangeability extends beyond kinetic energy to include potential energy as well. For example, in hydrogen fusion, when hydrogen nuclei combine to form a helium nucleus, a substantial amount of energy is released. Although the number of nucleons remains the same, the total rest mass of the nucleons decreases because the potential energy among hydrogen nucleons is greater than that among helium nucleons. The Sun undergoes this process continuously, generating the majority of the energy that sustains life on Earth.

Similarly, this interchange occurs in chemical reactions. Energy is released when high-potential-energy reactants convert into lower-potential-energy products, and the reverse process is also possible. For instance, plants on Earth absorb light energy from the Sun to produce more complex, energy-rich molecules, storing the absorbed energy in chemical bonds. The rest mass of substances changes slightly during these reactions; for example, a fully charged battery is slightly heavier than a discharged one. This difference is detectable with highly precise measurement instruments.

More directly, the energy contained in matter can be fully released, reducing its mass to zero. During positron-electron annihilation, the entire energy of the particles is converted into energy in electromagnetic radiation. Any fundamental particle can annihilate with its corresponding antiparticle, releasing the total energy of the mass. Conversely, in pair production, high-energy photons interacting near a nucleus can create an electron and a positron, forming matter from pure energy. These processes directly demonstrate the principle of mass-energy equivalence and their interchangeability.

The principle of mass-energy equivalence reveals the fundamental nature of any system and its matter, indicating that the majority of a system's internal energy is stored within its mass. Consequently, the total energy of a system can be expressed by Equation (1), forming the foundation of our revised definition of internal energy.

Dynamic Energy

Typically, the energy within a system is bound within matter and cannot be readily exchanged with its surroundings. Hydrogen, for instance, contains an enormous amount of energy, but this energy is usually inaccessible unless triggered by a nuclear reaction, as occurs in the Sun. The dynamic energy of a system refers to the portion of energy that can be exchanged both among its internal components and with its surroundings.

There are two main types of processes for releasing internal energy from a system. The first requires specific conditions to initiate, such as some chemical reactions and nuclear fusions. For example, some chemical reactions need a particular temperature, pressure, or a catalyst to proceed. The second type of process can occur spontaneously, such as nuclear fissions or electron orbital transitions.

For instance, consider an isolated vacuum container initially at absolute zero. Now, introduce high-temperature helium gas into the container. The electrons in the helium atoms tend to transition to lower energy orbitals, releasing potential energy as electromagnetic waves. This radiation is confined within the container, reflecting off its walls. Some of the electromagnetic waves may be reabsorbed by electrons, exciting them to higher orbitals. Over time, the level of radiation within the container will reach an equilibrium, where upward and downward electron transitions balance each other.

During this process, some energy is converted into particle kinetic energy through a mechanism termed “transimpact,” derived from “transition impact”.[11] When an electron absorbs energy and transitions to a higher orbital, the electron cloud expands, increasing the atom’s effective volume. This expansion reduces the spacing between adjacent particles, as shown in Figure 1B. This change disrupts the balance of van der Waals forces, creating short-range electrostatic repulsion that pushes adjacent particles apart, as illustrated in Figure 1C. These events unfold within nanoseconds, and the abrupt repulsion significantly boosts the kinetic energy of particle motion.

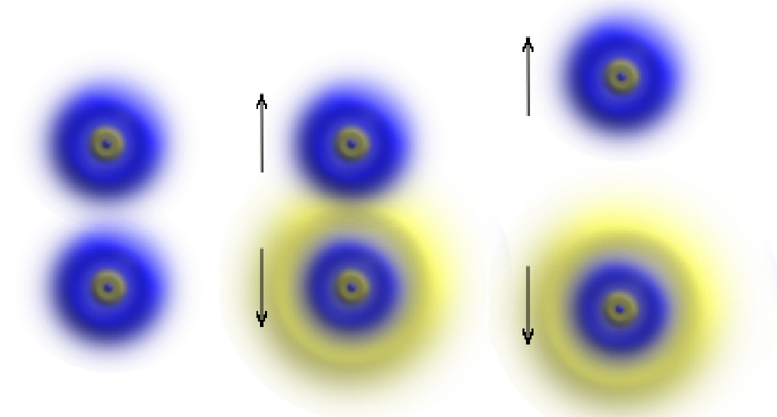

Figure 1, Transimpact due to a side effect of atomic electron transition.

To further illustrate the intensity and significance of transimpacts, let us consider the orbital transition process in a helium atom. A helium atom has two electrons, with a ground state configuration of $1s^2$. The radius of an atom is determined by the valence orbital. In the ground state, the helium atom’s radius is approximately *31 pm*. In the excited state, the configuration typically changes to $1s^1 2s^1$, with a radius of about *100 pm*. Thus, when a helium atom becomes excited, its radius more than triples, leading to a volume expansion of over *2600%* within a few nanoseconds.

A transimpact can be envisioned as the burst of popcorn. Imagine the momentum exerted on adjacent objects as they pop. Similarly, transimpacts are explosive and can impart significant momentum to adjacent particles, pushing them apart and causing vibrations. Since atomic electron transitions are common processes at the microscopic level and occur constantly in any substance, transimpacts should be prevalent interactions that affect many aspects of physics, particularly in thermodynamics. This process also provides the driving force for Crookes radiometers and Brownian motion.[12]

Transimpacts are capable of converting potential energy into kinetic energy in a system. Conversely, the motion or vibration of particles may collide with adjacent particles via electrostatic forces and “knock” their electrons into different orbitals, thereby causing them to radiate electromagnetic waves. Hence, the kinetic energy of particle motion is transformed into radiation. The radiation may be subsequently absorbed by other elections and stored as potential energy. Essentially, through these processes, kinetic energy is converted into both radiation and potential energy. Examples of kinetic energy being transferred to radiation and potential energy can be observed in many phenomena, such as friction heat.

Potential energy can also stored in bonds at different lengths. Bonds function like springs for energy storage. As the distance between atoms or molecules increases, the potential energy of the bond rises due to the work done in stretching it. Similar to electrons, bonds between atoms, as well as between nucleons, can also act as a reservoir for the dynamic energy within a system. Nuclear fission is another example of a spontaneous process that releases potential energy between nucleons.

Through these processes, some internal energy can be unlocked and dynamically exchanged among three forms: the potential energy of bonds, the kinetic energy of particles, and the energy of electromagnetic waves. These components will also eventually reach equilibrium. Although matter contains a vast amount of energy in various forms, including nuclear energy, dynamic energy typically represents only a small portion of its total energy.

Temperature and Thermal Energy

Electromagnetic waves radiated from a system constitute one of the three components of its dynamic energy. According to the Stefan-Boltzmann law, the power *P* emitted by a blackbody is directly proportional to the fourth power of its absolute temperature *T*:

$$(5) \qquad P = pT^4$$

where *p* is Stefan-Boltzmann's constant.[13-14] This equation provides the theoretical foundation for temperature-measuring devices. Infrared thermometers, for instance, determine temperature by detecting the average radiation level of electromagnetic waves emitted by a target object, allowing for non-contact measurement.

Stefan-Boltzmann's law can be derived from Planck's law[15-17] by integrating Planck's equation over frequency and then over the solid angle. Another direct consequence of the Planck radiation law is Wien's displacement of the peak wavelength of radiation: the black-body radiation curve for different temperatures peaks at a wavelength (λ) that is inversely proportional to the temperature:

$$(6) \qquad \lambda = \frac{b}{T}$$

where *b* denotes Wien's displacement constant. Wien's displacement law is evident in everyday experiences. For instance, an experienced baker can estimate the temperature of a stove by observing the color of the flame. This relation is often used to estimate the temperature of celestial bodies remotely. For instance, the peak emission of the Sun occurs at a wavelength of approximately *500 nm*, the surface temperature is *5,778 K* according to Wien's law.

The temperature measured with mercury thermometers also represents dynamic energy. When an electron in a mercury atom absorbs energy, it becomes excited to a higher orbital, causing the atom to expand and push adjacent atoms apart. This thermal expansion of mercury volume elongates the mercury column, which is then scaled to provide a temperature reading. This principle is also applied in other volume-based thermometers, such as alcohol thermometers.

Various thermometer designs utilize different mechanisms to detect properties related to a system's dynamic energy. For example, the electrical resistance of metals changes with temperature due to thermal expansion, a characteristic used in thermometers that measure temperature based on changes in electrical resistance.

Thus, temperature cannot represent the kinetic energy of a system. Instead, it reflects the system's dynamic energy, commonly referred to as thermal energy in the literature. Kinetic energy constitutes one of three components of dynamic energy, and it only indirectly relates to temperature when a system is in equilibrium. This indirect relationship leads to the misconception that temperature represents a system's kinetic energy, which complicates explanations of why temperature remains constant during a phase transition.

Although we might expect kinetic energy to increase as molecules gain freedom from intermolecular bonds during a phase transition, the temperature remains constant because it is governed by the potential energy associated with bonds. Temperature reflects the emission level of electromagnetic waves, which is directly influenced by potential energy. As a phase transition progresses, intermolecular bonds are broken, but the potential energy is constrained by the maximum stretch these bonds can withstand.[18] This constraint effectively stabilizes the dynamic portion of a system's potential energy, thereby holding the temperature steady until the transition is complete. Thus, kinetic energy can change during a phase transition, while temperature remains constant.

The Nature at Absolute Zero

Recognizing that temperature reflects the presence of dynamic energy helps clarify the concept of absolute zero. Now, let’s assume that the dynamic energy within a helium container can radiate outward, without any returning energy. As radiation levels drop, electrons will, on average, transition to lower orbitals, resulting in a decrease in potential energy, as well as kinetic energy. Eventually, all electromagnetic waves will radiate away, and electrons will settle into their lowest possible orbitals. With no further electron transitions to lower orbitals, no radiation can be detected, and temperature can no longer be registered.

Essentially, absolute zero temperature represents the point at which dynamic energy is no longer measurable, meaning no processes can access or release a system’s internal energy. This state may occur when all electrons are in their lowest energy orbitals, and molecular and intermolecular bonds are at their minimum lengths—conditions collectively known as the system’s "ground state”.

However, even this state may not guarantee the lowest possible emission level for a body containing radioactive elements. Therefore, reaching absolute zero also requires that the potential energy between nucleons be minimized. In this context, matter composed of iron can achieve this state. Because iron has the lowest potential energy between nucleons among all known elements, no nuclear reactions can occur within it to further release internal energy. This property partly explains why iron accumulates in regenerating stars.

Essentially, absolute zero requires the absence of any processes, especially spontaneous processes, that can release a system's internal energy. This means that all fundamental particles must occupy their lowest energy state, the ground state. It also requires the absence of conditions that could trigger processes, such as nuclear fusion or chemical reactions, that might unlock internal energy. However, electrons may still exhibit orbital motion, meaning that kinetic energy is not necessarily zero. Thus, absolute zero represents a state of minimum potential energy, not the minimum of kinetic energy.

Now, consider an isolated system with the total internal energy at its minimum, which we will refer to as the ground state energy or ground energy, denoted by E_0. Next, let's introduce some energy (E_t) to the system, such as photons. The light will bounce back and forth within the system. Some energy will be absorbed by particles in the system. For instance, electrons will absorb energy and become excited to higher orbitals. When an excited electron returns to a lower orbital, the stored energy is released, which may then be absorbed by other electrons. In the process, a certain fraction of the energy is converted to kinetic energy. Equilibrium among the three components of dynamic energy will be eventually established in the system. In this setting, this portion of energy (E_t) can be transferred and exchanged indefinitely within the system, representing the thermal energy of the system. The total internal energy of the system is therefore the sum of the ground energy and the thermal energy:

(7) $$E = E_0 + E_t$$

This equation represents an alternative decomposition of internal energy for a system, where the total internal energy of a system is also provided by the mass-energy equivalence principle in Equation (1), i.e., $E = mc^2$. Like electrons, various bonds, such as chemical and nuclear bonds, can also store potential energy. Together, they serve as the reservoir for the thermal energy or dynamic energy (E_t) of a system.

In an open system, this dynamic portion of internal energy (E_t) can be exchanged with its surroundings, allowing its temperature to be measured under the Zeroth law of thermodynamics. This dynamic energy is, in fact, responsible for most of the phenomena studied in thermodynamics.

Conclusions

Temperature measures thermal energy, which is primarily related to the potential energy component of a system's dynamic energy. Understanding thermal energy as the dynamic portion of internal energy is key to grasping the nature of temperature and absolute zero. Internal energy, defined as the total energy of a system by the mass-energy equivalence, can be divided into thermal energy and ground energy. At absolute zero, where a system reaches its ground state, no processes remain to further release internal energy, resulting in the absence of measurable dynamic or thermal energy, and thus an absolute zero temperature.

While kinetic energy is minimized at absolute zero, it does not vanish entirely, as electrons still exhibit orbital motion. Although kinetic energy is derived from potential energy and can equilibrate with it, this creates only an illusion of a direct relationship with temperature. Ultimately, temperature does not represent a system's kinetic energy.

See Also

- Is There a Sea of Free Electrons in Metals? (PDF)
- Unified Theory of Low and High-Temperature Superconductivity (PDF)
- Superfluids Are Not Fluids (PDF)
- Electron Tunnel (PDF)
- The Cause of Brownian Motion (PDF)

- The Process Driving Crookes Radiometers (PDF)
- Can Temperature Represent Average Kinetic Energy? (PDF)
- Why Phase Transition Temperature Remains Constant (PDF)
- Is Thermal Expansion Due to Particle Vibrating? (PDF)
- The Nature of Absolute Zero Temperature (PDF)
- Misconceptions in Thermodynamics (PDF)
- Superconductor Origin of Earth's Magnetic Field (PDF)
- Tidal Energy Is Not Renewable (PDF)
- How to Understand Relativity (PDF)
- The Simplest Derivation of $E = mc^2$ (PDF)
- Science vs. Mathematics (PDF)
- Potential Problems of AI Created Content (PDF)
- DeepSeek vs. ChatGPT at Advanced Levels (PDF)

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- 11/25/2023: Initial Post of This Article.
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